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This research program investigates the effect of extreme submicron and sub-100 nm spatial modulation of the electrostatic potential on the transport of electronis in heterojunction semiconductor devices. The test vehicle is the so-called periodic-gate FET (PGFET), with gate consisting of either a grating or a grid, of 200 nm periodicity. When electrons are made to move in a direction perpendicular to the potential modulation, i.e., perpendicular to the grating of along a grid axis, they exhibit a surface superlattice (SSL) effect. When moving along the potential modulation of a grating, electrons are restricted to only one degree of freedom and thus constitute a quasi-one-demsional (QID) quantum system. Grid-gate FET's have been found to exhibit substantially stronger SSL behavior than their grating-gate counterparts. Electron transport in quantized and spatially periodic systems have studied theoretically and new insights and quantitative calculations have been obtained.

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Study of Quantum Mechanical Effects in Deep Submicron Grating-Gate Field Effect Transistors

Annual Technical Report
for the period
1 October 1990 - 30 September 1991

Submitted by:
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December 1991

Study of Quantum Mechanical Effects in Deep Submicron, Grating Gate Field Effect Transistors

Annual Technical Report
Period: October 1, 1990 - September 30, 1991

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A. Objectives

This research program investigates the effect of extreme submicron and sub-100 nm spatial modulation of the electrostatic potential on the transport of electrons in heterojunction semiconductor devices. The test vehicle is the so-called periodic-gate FET (PGFET), with gates consisting of either a grating or a grid, of 200 nm periodicity. When electrons are made to move in a direction perpendicular to the potential modulation, i.e., perpendicular to the grating or along a grid axis, they exhibit a surface superlattice (SSL) effect. When moving along the potential modulation of a grating, electrons are restricted to only one degree of freedom and thus constitute a quasi-one-dimensional (Q1D) quantum system. Grid-gate FET's have been found to exhibit substantially stronger SSL behavior than their grating-gate counterparts. Electron transport in quantized and spatially periodic systems have been studied theoretically and new insights and quantitative calculations have been obtained.

Our studies have been expanded to include investigation of the planar resonant tunneling field-effect transistor (PRESTFET) as well as magneto-absorption, magnetocapacitance and magnetotransport in grid-gate MODFETs (in collaboration with Prof. D. Tsui's group at Princeton University). More recently, we have also started investigating device structures for studies of Coulomb blockade limited electron transport.

B. AlGaAs/GaAs PGFETs and Coulomb Blockade Structures

During the previous year, we have forged a fruitful collaboration with Keith Evans of Wright Paterson AFB. Dr. Evans has been providing us with some novel MBE layered heterojunctions in which the epilayers are grown not on a semi-insulating substrate, but on a heavily doped n^+ substrate. This configuration allows us to use the substrate as a second gate. The advantage of this scheme is that we now have the capability to independently set the confining potential seen by the electrons with the periodic top gate, while we sweep the electron density with the backgate. This type of decoupling will allow us to be much more quantitative in our analysis.

We have been working, in collaboration with Dr. Dieter Kern of IBM Yorktown Heights, to fabricate devices to study electron transport through isolated 'puddles' of electrons. Recently, it has been found experimentally that the conductance through such an electron 'puddle' can be modulated by two orders of magnitude, although such effects have been observed only at very low temperatures. The Coulomb charging effect responsible for this dramatic modulation of the conductance is one of the more promising quantum phenomena which might lead to practical device applications. Our goal is to use electron-beam lithography at IBM Yorktown to fabricate devices having puddles of size 01.-0.2 μm so that the charging energies will be large.

Recently, we have fabricated such devices using a partially etched AlGaAs doped layer approach to form 1-D channels and 1-D constricted channels. The novel aspect of our structure was that a uniform metal was deposited over the etched AlGaAs to act as a top gate. The structures worked well and did show clear ballistic contact quantum conductance steps, but no Coulomb blockade conductance steps have been observed yet. Characterization of these devices at 300 mK is continuing.

We used the Si MOS, dual split-gate configuration to compare the magnetoconductance of many parallel narrow inversion channels, a modulated 2 D potential, and a uniform 2 D electron gas. Electron weak localization becomes much more pronounced as the device is electrostatically pinched from a two dimensional inversion layer into many narrow wires in parallel, proving that the wire width can be reduced below the electron phase coherence length. For magnetic fields greater than 1 Tesla normal to the sample surface there is a large drop in the current of 90% or more, and which persists to room temperature, as electrons are added to the device so that it opens electrostatically from many narrow inversion layers in parallel into a two-dimensional electron gas. This large negative transconductance results from electrostatically changing the dominant boundary condition on the classical Drude magnetoconductance tensor from that of a long and narrow to a short and wide conductor. Quantum edge states form at high magnetic fields, giving opposite high-field magnetoconductance for the parallel wires and wide electron gas. At a magnetic field of 30 Tesla the two-terminal conductance versus gate voltage of the narrow wires evolves into quantum Hall steps having a height of $2e^2/h$ multiplied by the number of wires in parallel. In contrast to a wide device, the conduction band valley degeneracy is not resolved, giving rise to Hall steps of twice the expected size. The evolution from Shubnikov-de Hass oscillations to the quantum Hall effect qualitatively reproduces the 'anomalous magnetoresistance' of Kastner *et al.*

In a new initiative we are investigating quantum wires defined by anisotropic etching and metal-organic chemical vapor deposition (MOCVD). Optical and transport properties of these wires will be studied. We can combine these wire structures with our grating-gate technology to study the transition between Q1D and Q0D regimes. Furthermore, the nanofabrication techniques can be used to define quantum dots and so-called 'anti-dot' structures. At this point we are still evaluating the anisotropic etch process.

During the past year, we improved the technique of achromatic holographic lithography (AHL) for generating 100 nm-period gratings and grids (50 nm lines and spaces). A novel antireflective coating has been designed for use with PMMA, the resist used in AHL. As a result, we are now able to obtain grating lines of high contrast in

PMMA. All this will greatly improve the quality of the second-generation x-ray masks while reducing the number of processing steps in their fabrication.

C. The PRESTFET

We have succeeded in making first generation PRESFET x-ray masks using both focused-ion beam lithography and high-voltage (50 kV) electron-beam lithography. In both cases, 50 nm line-and-space patterns were generated using a single-resist-layer scheme. This single-step process ensures high yield. The first generation masks were replicated onto second generation, reversed-polarity masks using contact x-ray lithography. We are currently aligning masks to patterns on GaAs substrates using a modular insert attached to a conventional UV alignment tool. We have previously demonstrated sub-0.5 micron alignment using this system. Fig. 1 shows a micrograph of a PRESTFET gate configuration replicated in our new proximity x-ray mask aligner.

The focused-ion-beam work discussed in the previous paragraph was done at MIT, and the e-beam lithography work was done in collaboration with IBM. We are currently collaborating with the Naval Research Laboratory to make x-ray masks with sub-100 nm features using a 50 kV electron beam.

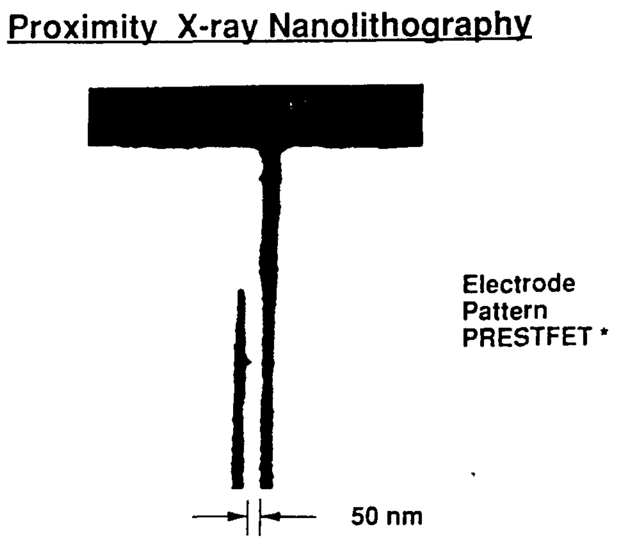

Fig. 1 Electron micrograph showing replication via x-ray nanolithography, of 50 nm lines and spaces at a mask-to-substrate gap of 2.72 μm using the 1.34 nm x-ray. This demonstrates the viability of manufacturing-compatible lithography at 50 nm features.

D. Modeling of Quantum Transport

The modeling of QEE structures and devices is important both in understanding the basic features and limitations as well as in simulating devices to perform special functions. We have developed a modeling scheme which gives a unified method of understanding how quantum effects are affected by temperature, mobility, voltage, and geometrical structure. This model provides not only a qualitative understanding of the various quantum phenomena, but also a basis for developing efficient numerical algorithms for modeling specific devices. We have called this scheme the convolution method because most of the calculations can be written in terms of separate convolutions involving the individual phenomena of temperature, mobility, voltage and geometrical structure. We have successfully used the convolution model to develop general observability criteria for quantum devices as well as model the current-voltage characteristics of specific devices such as the surface superlattice resonant tunneling devices of various dimensions, and single quantum wires.

An important parameter in modeling is the scattering time or, equivalently, the transmission through the impurity potential. Recently, two of our students, Avind Kumar and Phil Bagwell have overthrown many preconceived ideas about scattering in quantum devices with reduced dimensionality. They have shown that evanescent modes dramatically change the nature of impurity scattering and, hence, the conductance. In short, impurity scattering cannot be treated within the Born approximation as is done in all calculations of the scattering times for 3D systems. Arvind Kumar and Phil Bagwell have shown that the scattering potential couples the propagating modes to the evanescent modes, thereby causing electron density to accumulate locally around the impurity defect, as shown in Figure 2. Furthermore, the accumulation of electron probability near the impurity by the evanescent modes is greatly affected by the sign of the impurity potential. Figure 3 shows how the quantized conductance steps are affected by the evanescent modes. The repulsive potential simply rounds out the corners on the quantized conductance steps; whereas, the attractive potential introduces a sharp dip in conductance before the opening of each new subband. The standard treatment without evanescent modes would have not shown the structure due to the attractive potential.

The convolution method and the insight about impurity scattering from evanescent modes will lead not only to developing the basic understanding of quantum-effect electronics but also to device simulators needed to design circuits.

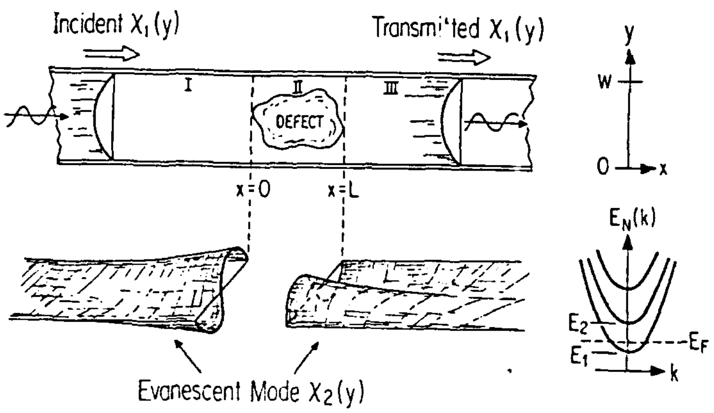

Fig. 2 Scattering from a defect in a quasi-one-dimensional wire where a steady current incident in the lowest mode is applied from the left. The scattering potential couples the incident propagating mode to the evanescent modes, causing probability density to accumulate locally around the defect.

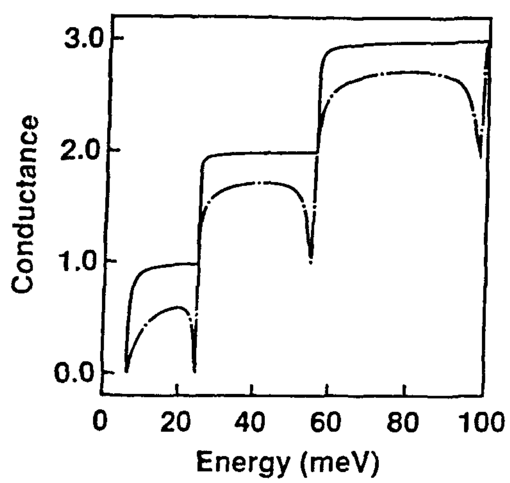

Fig. 3 Conductance through a single scatterer in a quasi-one-dimensional wire as a function of Fermi energy. The two curves give the conductance through a repulsive defect (solid) and an attractive defect (dashed).

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